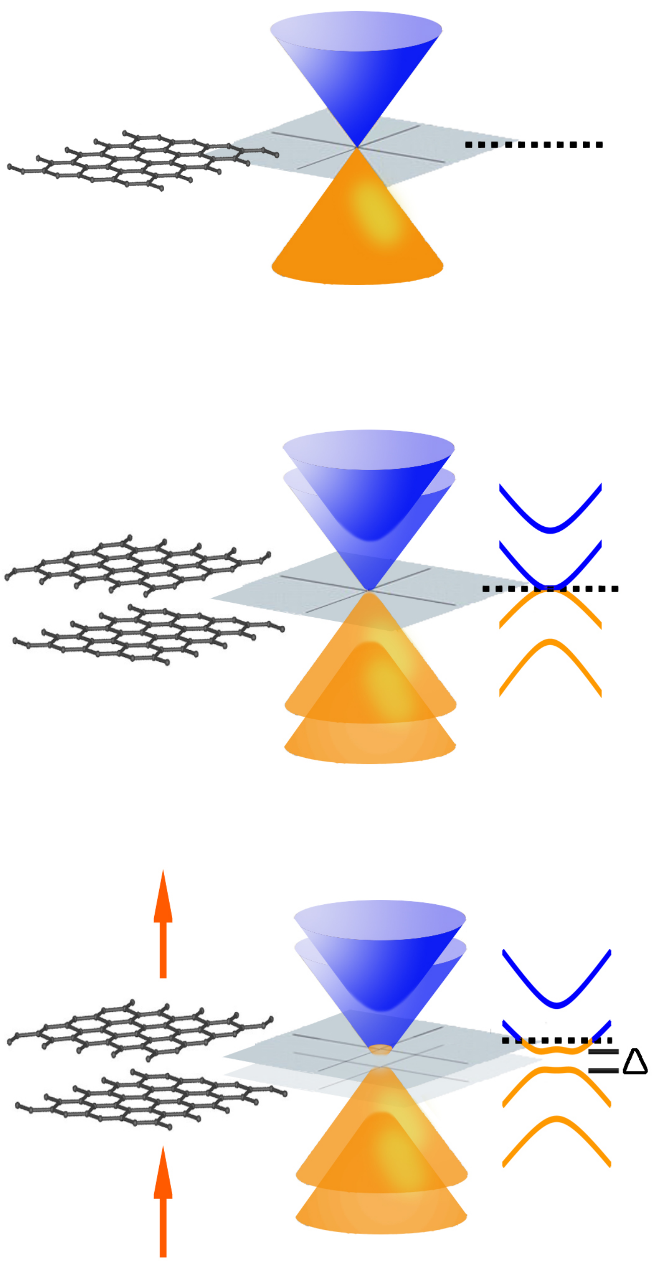
# A tunable graphene bandgap opens the way to nanoelectronics and nanophotonics

Graphene's electrical properties include electrons so mobile they travel at near light speed. But without a bandgap, graphene's promise for electronics and photonics can't be realized. Now researchers can precisely tune a bandgap in bilayer graphene from zero to the infrared.




One of the most unusual features of single-layer graphene (top) is that its conical conduction and valence bands meet at a point – it has no bandgap. Symmetrical bilayer graphene (middle) also lacks a bandgap. Electrical fields (arrows) introduce asymmetry into the bilayer structure (bottom), yielding a bandgap (Δ) that can be selectively tuned.

BERKELEY, CA – Graphene is the two-dimensional crystalline form of carbon, whose extraordinary electron mobility and other unique features hold great promise for nanoscale electronics and photonics. But there's a catch: graphene has no bandgap.

"Having no bandgap greatly limits graphene's uses in electronics," says Feng Wang of the U.S. Department of Energy's Lawrence Berkeley National Laboratory, where he is a member of the Materials Sciences Division. "For one thing, you can build field-effect transistors with graphene, but if there's no bandgap you can't turn them off! If you could achieve a graphene bandgap, however, you should be able to make very good transistors."

Wang, who is also an assistant professor in the Department of Physics at the University of California at Berkeley, has achieved just that. He and his colleagues have engineered a bandgap in bilayer graphene that can be precisely controlled from 0 to 250 milli-electron volts (250 meV, or .25 eV).

Moreover, their experiment was conducted at room temperature, requiring no refrigeration of the device. Among the applications made possible by this breakthrough are new kinds of nanotransistors and – because of its narrow bandgap – nano-LEDs and other nanoscale optical devices in the infrared range.

The researchers describe their work in the June 11 issue of *Nature*.

**Constructing a bilayer graphene transistor**

As with monolayer graphene, whose carbon atoms are arranged in "chickenwire" configuration, bilayer graphene – which consists of two graphene layers lying one on the other – also has a zero bandgap and thus behaves like a metal. But a bandgap can be introduced if the mirror-like symmetry of the two layers is disturbed; the material then behaves like a semiconductor.

Previously, in 2006, researchers at Berkeley Lab's Advanced Light Source (ALS) observed a bandgap in bilayer graphene in which one of the layers was chemically doped by adsorbed metal atoms. But such chemical doping is uncontrolled and not compatible with device applications.

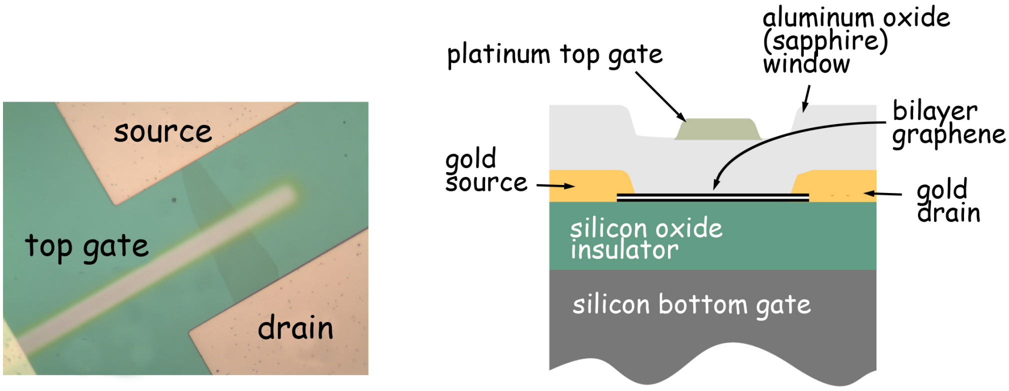
"Creating and especially controlling a bandgap in bilayer graphene has been an outstanding goal," says Wang. "Unfortunately chemical doping is difficult to control."

Researchers then tried to tune the bilayer graphene bandgap by doping the substrate electrically instead of chemically, using a perpendicularly applied, continuously tunable electrical field. But when such a field is applied with a single gate (electrode), the bilayer becomes insulating only at temperatures below one degree Kelvin, near absolute zero – suggesting a bandgap value much lower than predicted by theory.

Says Wang, "With these results it was hard to understand exactly what was happening electronically, or why."

Wang and his colleagues made two key decisions that led to their successful attempt to introduce and determine a bandgap in bilayer graphene. The first was to build a two-gated bilayer device, fabricated by Yuanbo Zhang and Tsung-Ta Tang of the UC Berkeley Department of Physics, which allowed the team to independently adjust the electronic bandgap and the charge doping.

The device was a dual-gated field-effect transistor (FET), a type of transistor that controls the flow of electrons from a source to a drain with electric fields shaped by the gate electrodes. Their nano-FET used a silicon substrate as the bottom gate, with a thin insulating layer of silicon dioxide between it and the stacked graphene layers. A transparent layer of aluminum oxide (sapphire) lay over the graphene bilayer; on top of that was the top gate, made of platinum.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drain
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